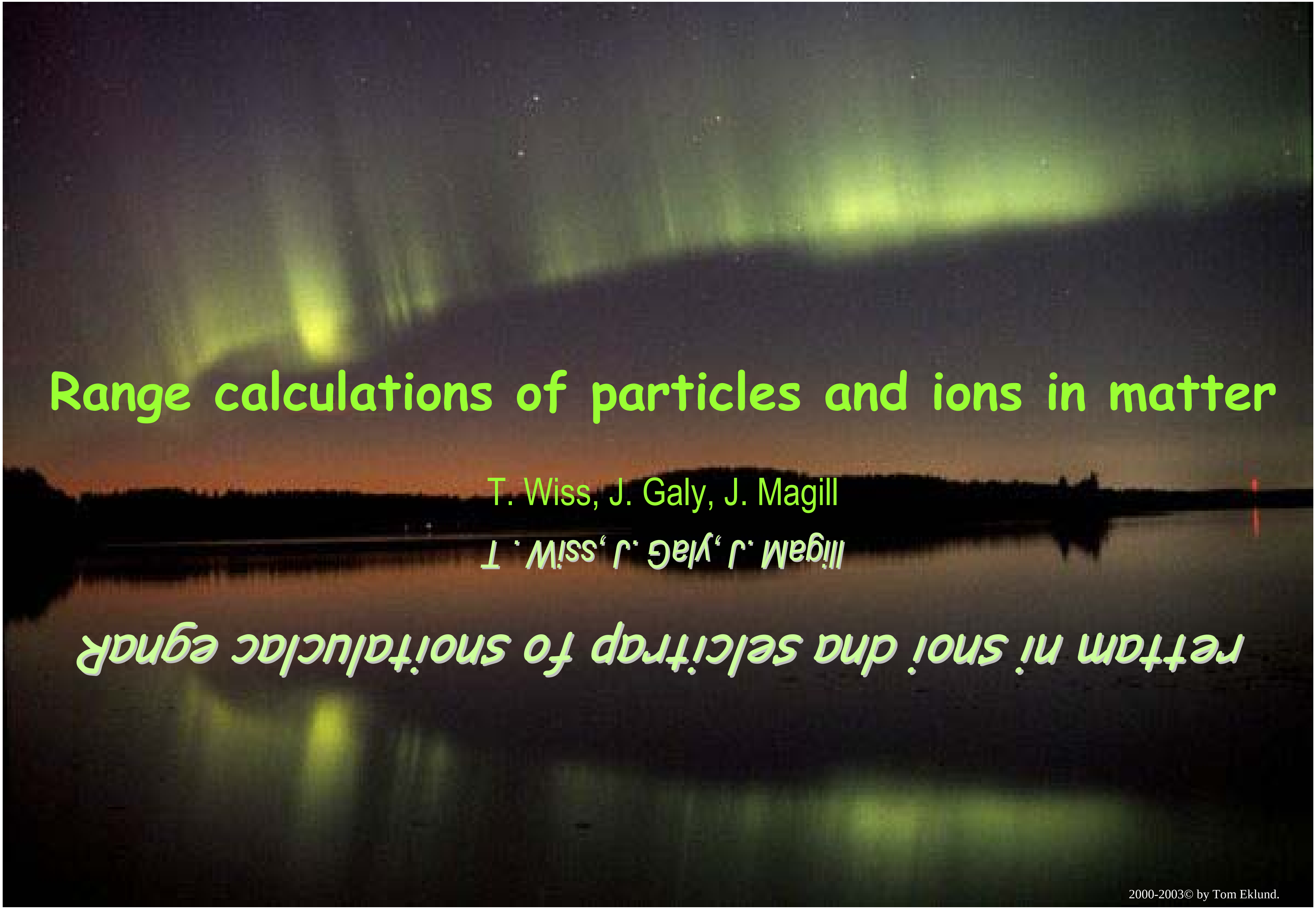
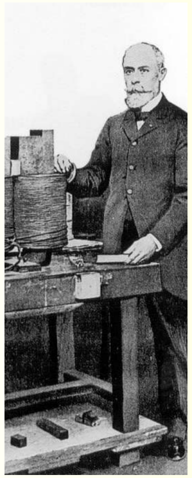
Range calculations of particles and ions in matter

T. Wiss, J. Galy, J. Magill



Some pioneers…

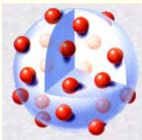
"Les rayons alpha sont des projectiles matériels susceptibles de perdre de leur vitesse en traversant la matière" (1900)

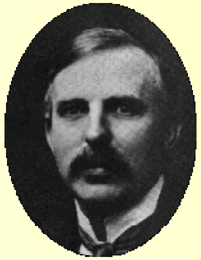


H. Becquerel

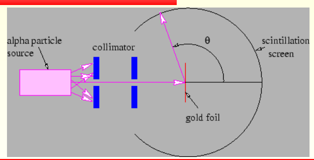
P. Curie

M. Curie-Slodowska

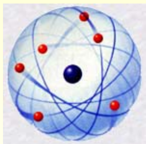




E. Rutherford

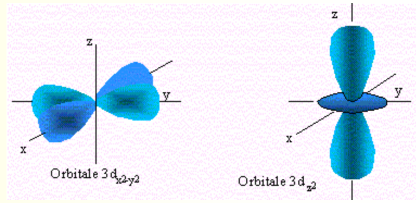


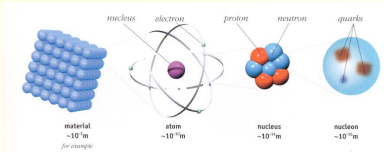
N. Bohr



E. Fermi

E. Schrödinger





1896 — 1911 — today….

Joint Research Centre

Particle/ion-matter interactions

Slowing down of a particle/ion in a target

• history of the particle

energy loss of a particle, *range*, interactions

• history of the target atoms

displacements, recombinations, ionization, excitation, radiation damage build-up

Areas of interest

Nuclear industry, nuclear medicine, space applications, semi-conductor, geology...

Joint Research Centre

Interaction of a charged particle with matter

Inelastic collisions with an electron
    main process of energy loss producing excitation and ionization

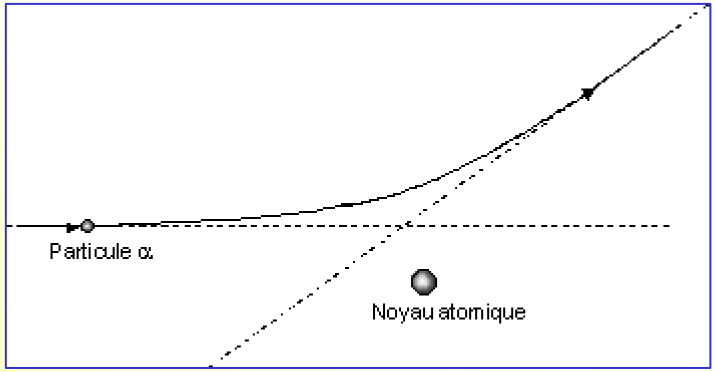
Inelastic collisions with a nucleus
    Bremsstrahlung and coulombic excitation

Elastic collisions with a nucleus
    Rutherford diffusion

Elastic collisions with an electron

Rutherford diffusion

$$\frac{1}{2}M_1v_1^2 = \frac{1}{4\pi\varepsilon_0}\frac{Z_1Z_2e^2}{D}$$



D was measured by Rutherford.
The minimum D value indicated

the upper limit of the nuclei radius.

- Many interactions are needed to stop the particle (low probability of energy transfer).

- the probability to transfer energy is inverse to the mass of the target particle (mainly electrons will participate).

- Probability higher at low velocity (end of range).

Nuclear stopping power

Analytical description by Biersack $-\left.\frac{dE}{dx}\right)_n = T.d\sigma_s(E_1, T) = 4\pi N a_{TF}\left(\frac{M_1}{M_1+M_2}\right) Z_1 Z_2 e^2 \frac{\log(\varepsilon)}{2\varepsilon\left(1-\varepsilon^{-1.49}\right)}$

For ion energies below 0.1 MeV predominant process

Electronic stopping power

Electronic collisions constitutes inelastic interactions where electrons can be exchanged between incident ions and target atoms. The corrected Bethe and Bloch formula is adequate for particle velocity larger than the velocity of the minimum-bound electrons.

$$-\left.\frac{dE}{dx}\right)_e = nZ_2 \frac{4\pi}{m_e v_2^2}\left(\frac{Z_1^* e^2}{4\pi\varepsilon_0}\right)^2 \left[\ln\left(\frac{2mv^2}{I}\right) - \beta^2 - \ln\left(1-\beta^2\right) - \frac{C}{Z^2}\right]$$

For lower velocities the electron clouds can re-organize them. Lindhard and Scharff proposed an expression for the electronic stopping power based on the TF atom.

Stopping power for electrons

For beta decays the energy distribution is a continuum with $E_{ßmax}$
Typically 2.6 keV < E < 10.4 MeV

e^- and e^+ produce ionisation and excitation along their path.
Nuclear scattering is very large

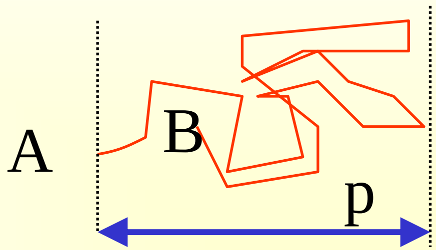
Rutherford scattering cross-section is proportional to $(M_1/m_0)^2$
$\sigma_{e-}/\sigma_{p+} = 4\ 10^6$

In fact σ can be extremely large and target e- have to be considered.

For very high energy, accelerated particles loses part of their energy radiatively as „Bremstrahlung" (govern by the Maxwell equations).
At the origin of synchrotron radiation.

Range of electrons

Difficult to assess because of the numerous scattering event (even backscattering). Rather than range, penetration depth.



Range = AB

p : penetration depth

The Z of the target has less influence since the ratio between real range and absorption thickness increases with Z but ionisation diminish.

Empirical formulation by Katz and Penfold (1952).

•10 keV < E < 3 MeV

$R\ (mg.cm^{-2}) = 412\ E^{n}$ with $n = 1.265 - 0.0954 \log E$

•1 MeV < E < 20 MeV

$R = 530\ E - 106$

Range of particles

For two particles A and B with the same velocity in the same material

$R_A = (M_A/M_B)x(Z_B/Z_A)^2R_B$ e.g. $R_d/R_p = 2$ $R_t/R_p=3$

Rule of Bragg and Kleeman

For different materials

$R_1/R_2 = \rho_2/\rho_1(A_1/A_2)^{1/2}$ approximation by 15%

Range of alpha-particles

Range of α in air

$E_\alpha<4$ MeV

$R_{\alpha,air} \sim 0.56\ E_\alpha$

4MeV < E < 8 MeV

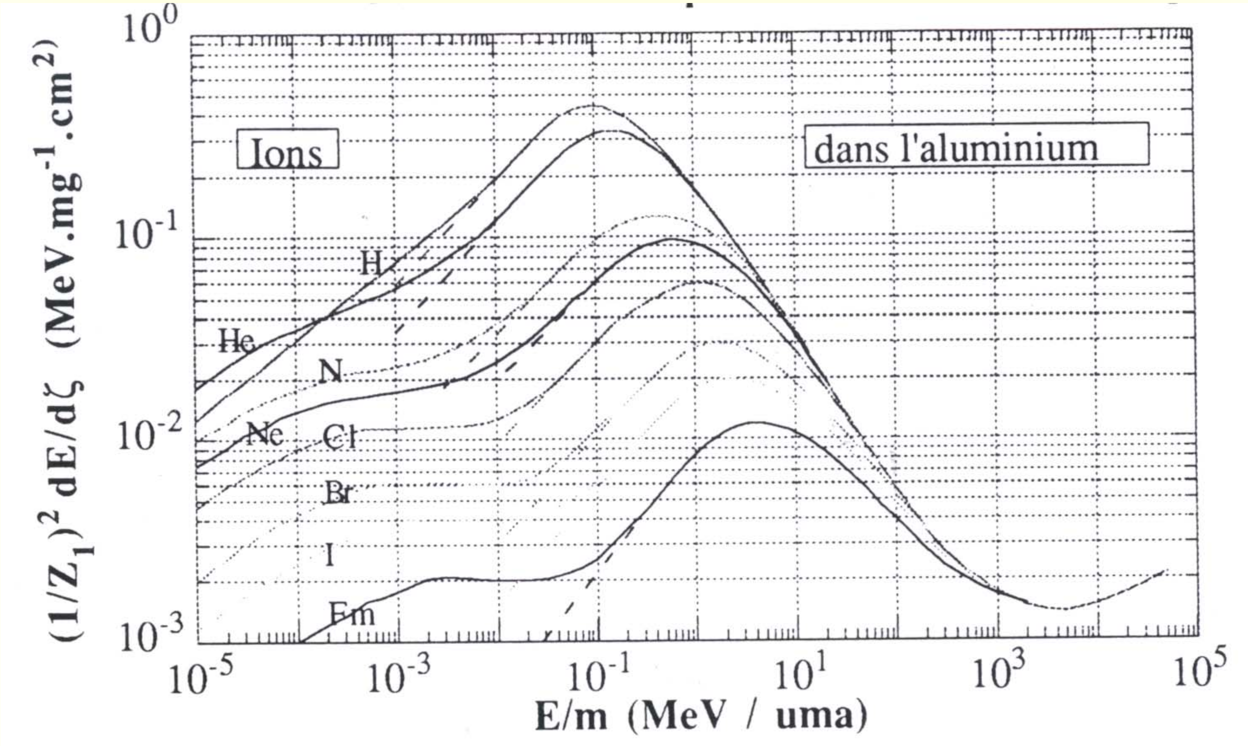
$R_{\alpha,air} \sim 1.24\ E\alpha - 2.62$

In other media

$R_\alpha \sim 5.6\ 10^{-4}\ A^{1/3}\ R_{\alpha,air}/\rho_{medium}$

Range of heavy ions

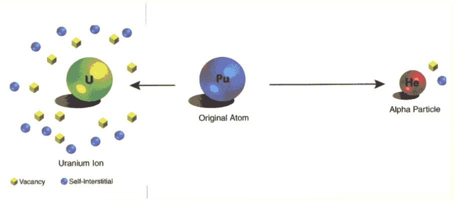
The stopping power for heavy ion can be assessed by the Bethe-Bloch approach but needs to be corrected by the effective charge (dependant on the velocity).



At high energy the curves of the heavy ions join the one of the proton.

From one medium to another Z/A correction.

Range of different particles

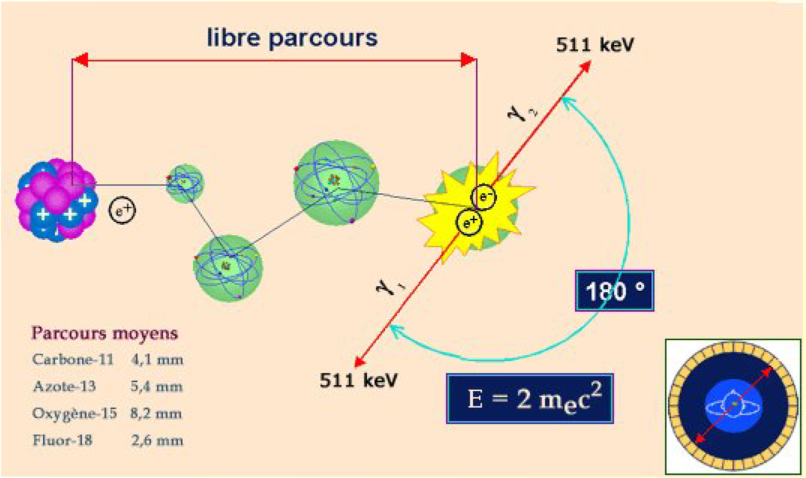


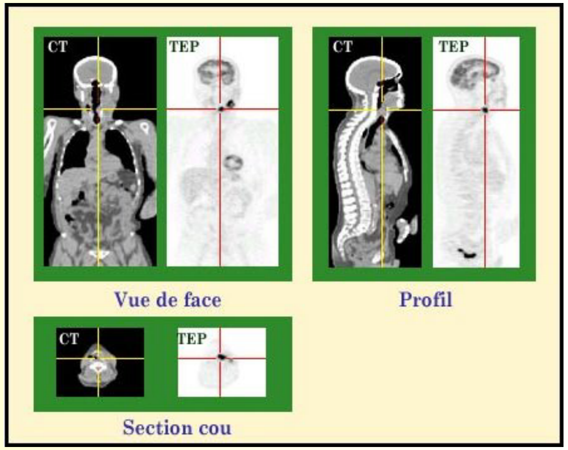
	Energy, keV	Range, µm	dE/dx, Nucl./Elec.	Defects formed
Light FPs	95000	9	0.03/0.97	40000
Heavy FPs	67000	7	0.06/0.94	60000
α-particles	5000	12	0.01/0.99	200
Recoil nucleus	95	0.02	0.90/0.10	1500
Cosmic rays (p^+)	10^{17} 10^{6} (typical)	Light years !		

Particles	Origin	Use
e^-	Cosmic rays	medicine
n	Radioactivity	industry
p^+	- natural	research
d^+	- artificial	radioprotection
α	Accelerators	
heavy ions		

Positron Emission Tomography

Injection of fluorodesoxyglucose (FDG) marqued by fluor-18 allows to trace glucose consumption by tissues. This is particularly significant by cancerous tissues.

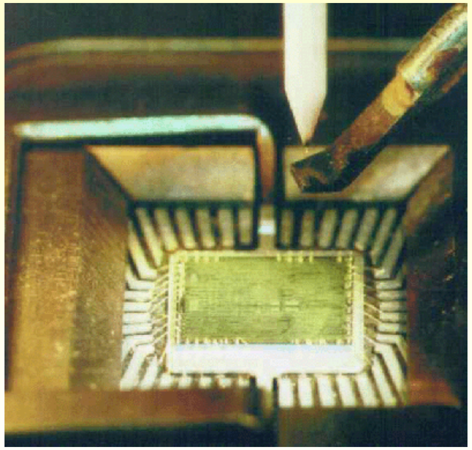




Isotope	Half live (minutes)	Emax β+(keV)	Mean projected range (mm)
^{18}F	110	630	2,6
^{11}C	21	960	4,1
^{13}N	10	1200	5,4
^{15}O	2	1730	8,2

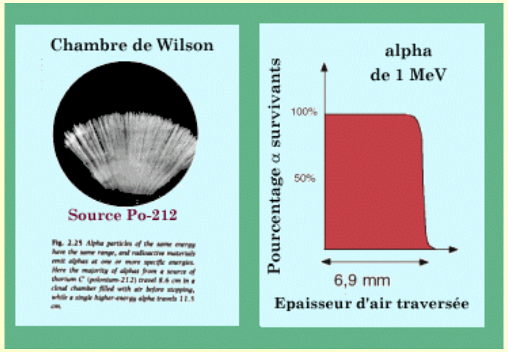
Junctions in semi-conductors

The majority of integrated circuits are fabricated from single crystal silicon wafers doped with Group III elements (B, Al, Ga, In ,Tl), p-type, or with Group V elements (N, P, As, Sb, Bi), n type. Transistors are formed by junctions between n-type and p-type silicon in the sequences n-p-n or p-n-p. Dopants are impurity elements added to the semiconductor crystal to form electrical junctions or boundaries between "n" and "p" regions in the crystal. The most common doping methods include diffusion and **ion implantation**.



Radioprotection - Shielding from radioactive sources

- Assess the thickness of a shielding: 40 µm of Al for most of the alpha-emitters

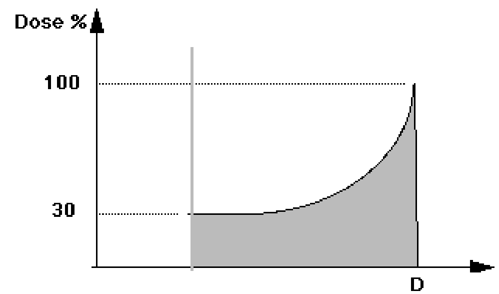


- C^{14} 0.156 MeV beta (maximum) Range 24 cm in air unshielded

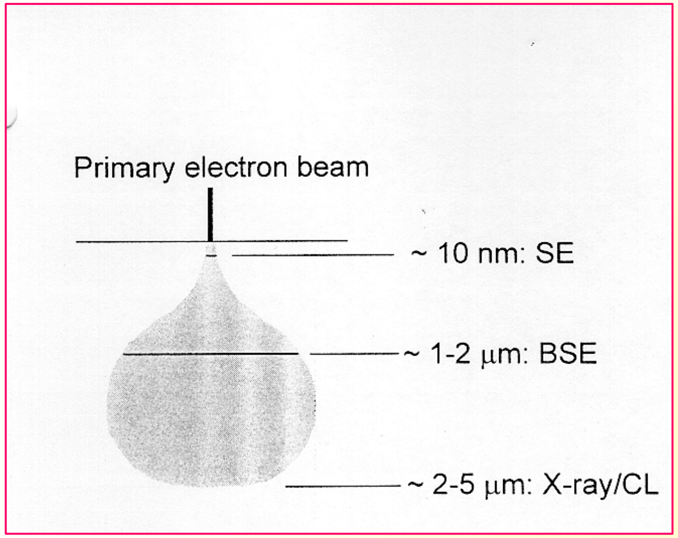
Plexiglas 1 cm thick is recommended as shielding material.

- Protontherapy

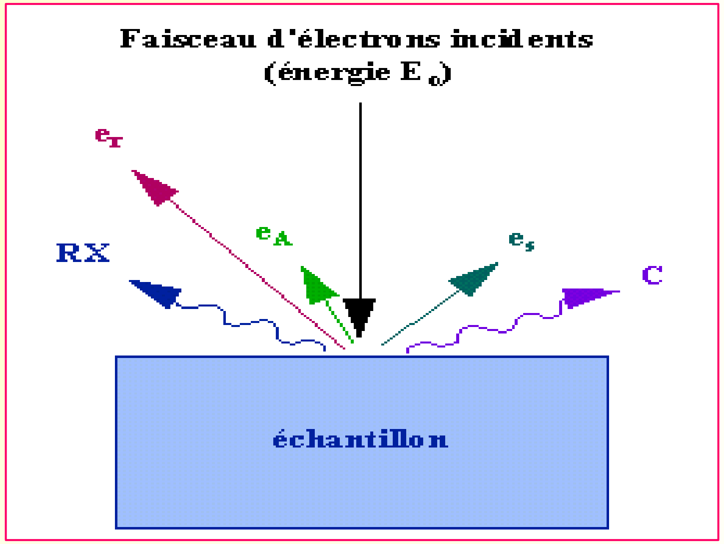
200 MeV p+ can penetrate in 22 cm tissue



EDX analysis: knowing the range of electrons



e_r: backscattered electrons
e_s: secondary electrons
e_A: Auger electrons
RX: x-rays



Knowing the « range » of electrons helps to avoid geometrical artifacts

Database compiling stopping power and ranges

- International commission on radiation units and measurements, inc.

ICRU Report 49, *Stopping Power and Ranges for Protons and Alpha Particles*

- National Institute for Standards and technology, NIST

ESTAR, PSTAR, and ASTAR

Range calculation in Nuclides.net©

- New module RANGE to be implemented in Nuclides.net v2 (mid-2006)
- Ionized particles ranges and stopping power calculated with SRIM
- Electron stopping power based on the Bethe-Block equation

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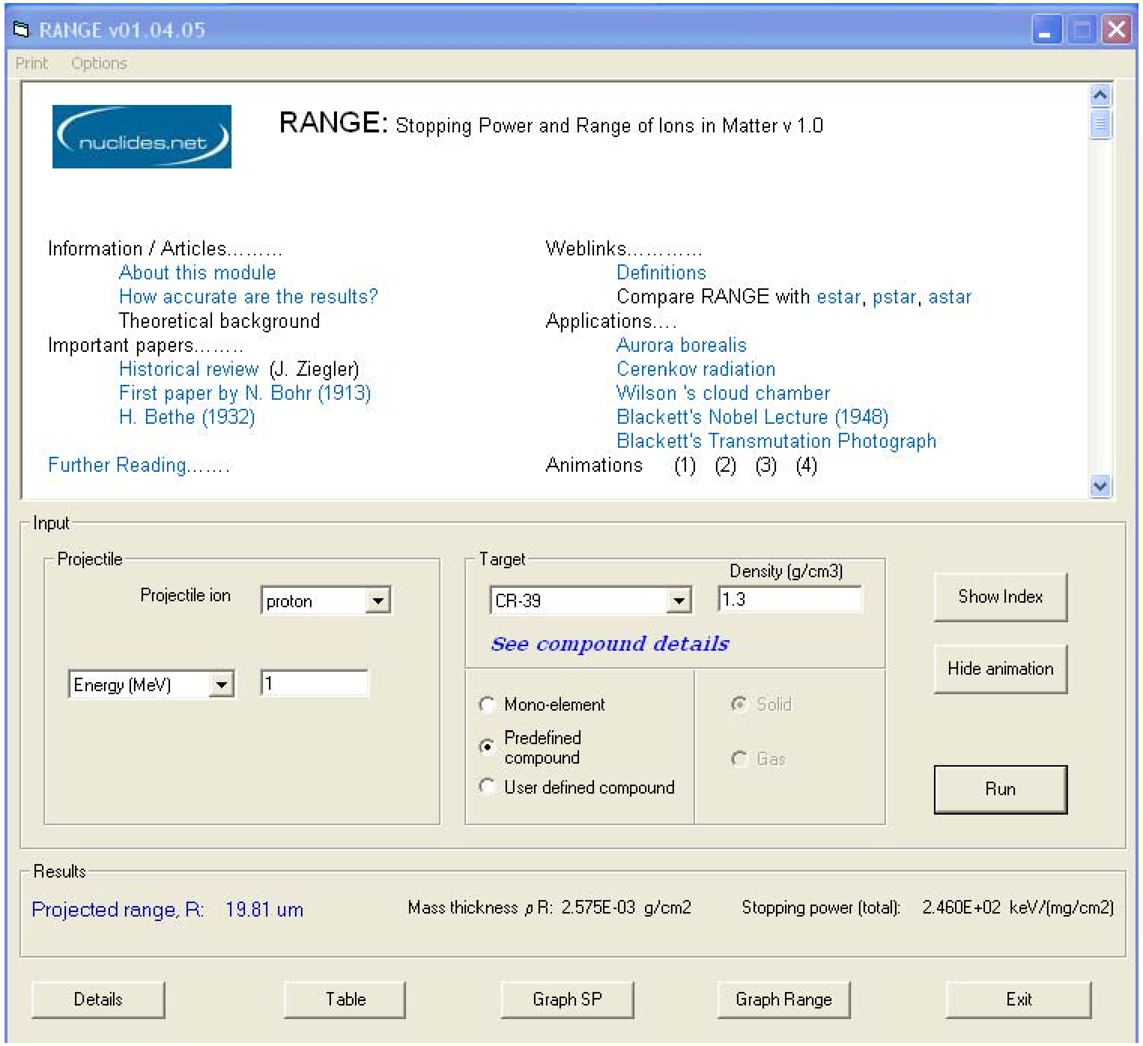

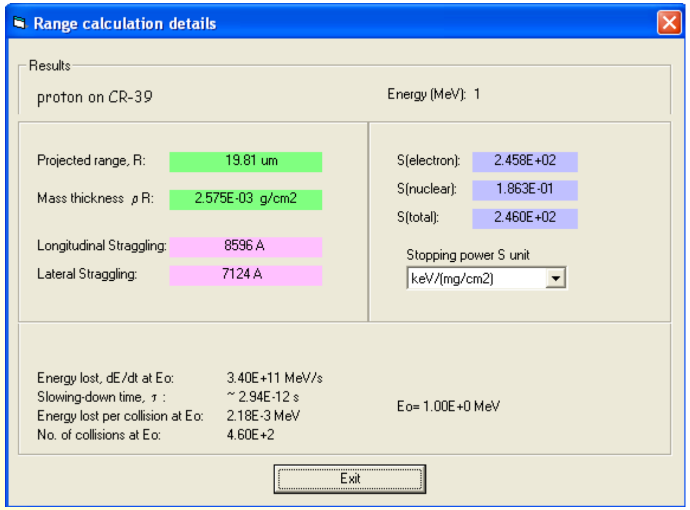

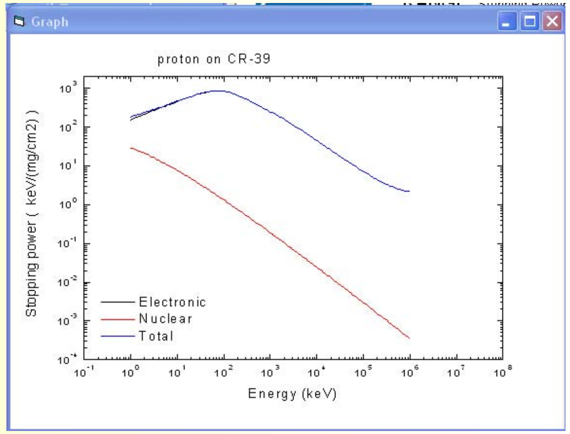

Ion Energy	dE/dx Elec.	dE/dx Nuclear	Projected Range	Longitudinal Straggling	Lateral Straggling
999.999 eV	1.541E+02	2.866E+01	265 A	169 A	139 A
1.10 keV	1.616E+02	2.751E+01	290 A	180 A	148 A
1.20 keV	1.688E+02	2.647E+01	314 A	190 A	157 A
1.30 keV	1.757E+02	2.551E+01	338 A	200 A	166 A
1.40 keV	1.823E+02	2.464E+01	362 A	209 A	175 A
1.50 keV	1.887E+02	2.384E+01	386 A	217 A	183 A
1.60 keV	1.949E+02	2.310E+01	410 A	226 A	191 A
1.70 keV	2.009E+02	2.241E+01	433 A	233 A	199 A
1.80 keV	2.067E+02	2.177E+01	457 A	241 A	206 A
2.00 keV	2.179E+02	2.062E+01	502 A	255 A	221 A
2.25 keV	2.298E+02	1.937E+01	559 A	272 A	238 A
2.50 keV	2.411E+02	1.828E+01	614 A	287 A	253 A
2.75 keV	2.518E+02	1.733E+01	668 A	300 A	268 A
3.00 keV	2.620E+02	1.649E+01	721 A	313 A	283 A
3.25 keV	2.718E+02	1.574E+01	774 A	325 A	296 A

Institute for Transuranium Elements